Astronomy & Astrophysics manuscript no. 2134txt February 5, 2008
(DOI: will be inserted by hand later)

HS 2134+0400 - new very metal-poor galaxy, a representative of void population?

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Received July 18, 2005; accepted 2005

Abstract. We present the SAO 6 m telescope spectroscopy of a blue compact galaxy (BCG) HS 2134+0400 discovered in frame of the dedicated Hamburg/SAO survey for Low Metallicity BCGs (HSS-LM). Its very low abundance of oxygen (12+log(O/H) = 7.44), as well as other heavy elements (S, N, Ne, Ar), assigns this dwarf galaxy to the group of BCGs with the lowest metal content. There are only eight that low metallicity among several thousand known BCGs in the nearby Universe. The abundance ratios for the heavy elements (S/O, Ne/O, N/O, and Ar/O) are well consistent with the typical values of other very metal-poor BCGs. The global environment of HS 2134+0400 is atypical of the majority of BCGs. The object falls within the Pegasus void, the large volume with the very low density of galaxies with the normal (M^{*}_{B}=–19.6) or high luminosity. Since we found in voids a dozen more the very metal-poor galaxies, we discuss the hypothesis that such objects can be representative of a substantial fraction of the void dwarf galaxy population.

Key words. galaxies: dwarf – galaxies: evolution – galaxies: abundances – galaxies: individual: HS 2134+0400 – large-scale structure of universe

1. Introduction

The heavy element contents in a galaxy interstellar medium (ISM) is the parameter characterizing the current evolutionary state of a galaxy. There is a general correlation between Z - the metallicity of ISM (often described in terms of the oxygen abundance O/H) and the galaxy mass, in sense, that the massive, luminous galaxies (with luminosities of L_* and higher) have the characteristic values of O/H of about solar value[1] or a few times higher. Low-mass, subluminous galaxies have rather wide O/H distribution, with the great majority of known O/H-values to be in the range of 1/10 to 1/2 of the solar value (e.g., Kunth & Östlin 2000 and references therein and new data in Kniazev et al. 2004). In very small fraction of dwarf galaxies ($\lesssim$2%), the Z(ISM) is in the very low metallicity regime, conditionally accepted as $Z < Z_{\odot}/10$, or 12+log(O/H) $\leq$7.65 (e.g., Kunth & Östlin 2000). We call them eXtremely Metal-Deficient (XMD) galaxies. The blue compact galaxy (BCG) I Zw 18 (Searle & Sargent 1972), with 12+log(O/H)=7.17 (e.g., Izotov & Thuan 1999) was known during more than 30 years as the most metal-poor object in the nearby Universe. Recently Izotov and Thuan (2005) have shown that another well known galaxy SBS 0335–052 W, discovered in 1997 (Pustilnik et al. 1997), is even more metal-poor, with the oxygen abundance of 12+log(O/H)=7.12.

Despite such galaxies are very rare in today's Universe, they are interesting, on one hand, as the representatives of groups with less typical evolution paths. On the other hand, many processes in the ISM, including the star formation (SF) and the interaction with massive stars, do strongly depend on the ISM metallicity. Therefore, the detailed study of the rare XMD galaxies can help in the understanding of galaxy formation and their early evolution in the high-redshift Universe, at the epochs when such galaxies were much more typical.

The very low ISM metallicity in the local galaxies can be a result of various evolutionary scenarios. They include: a) a significant metal loss due to a powerful galactic superwind related to starbursts, b) the dilution of the accumulated in the ISM metals due to the inflow of the intergalactic gas (or the infall of intergalactic clouds) with the 'pregalactic' metal content; c) a very slow gas consumption rate and, respectively, a low metal production rate in some galaxies, such as very low surface-brightness (LSB) galaxies; and d) a very large delay in the SF onset,

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[1] According to the recent updates, the solar value of O/H is accepted as 12+log(O/H)=8.66 (Asplund et al. 2004).

corresponding to the recent first SF episodes in very stable protogalaxies. Only the latter option results in a truly young galaxy in the local Universe.

Such interesting objects seem to exist among the known XMD galaxies, but only a few reliable candidates for young galaxies are identified to date. The best known candidate is the BCG I Zw 18, for which Izotov & Thuan (2004a) have shown from the analysis of its very deep Hubble Space Telescope colour-magnitude diagram that the oldest stars in this galaxy have ages $T \leq 500$ Myr (see also Östlin & Mouhcine 2005). The other most probable candidate for young galaxies include first of all the objects with the least known ISM metallicities (12+log(O/H) $\leq$ 7.29): the components of the unique binary system (with the mutual projected distance of 22 kpc) SBS 0335–052 E and W (Izotov et al. 1999, Lipovetsky et al 1999, Pustilnik et al. 2001a, 2004a; Izotov & Thuan 2005) and the nearest such galaxy, DDO 68 (Pustilnik et al. 2005a).

To understand better the properties and the evolution status of XMD galaxies, one needs in a sufficiently large sample of such objects. Despite their paucity, there was a significant progress in the identification of new XMD galaxies during the recent decade, mainly due to the large surveys of emission-line galaxies, such as the Second Byurakan (SBS), Hamburg-SAO for ELGs (HSS), Kitt Peak International Spectral (KISS), Hamburg-SAO for Low Metallicity BCGs (HSS-LM). The significant number of new XMD galaxies is also found among the objects of Sloan Digital Sky Survey (Kniazev et al. 2003). Their current number is about a half hundred.

One of the surveys aimed at the search for new XMD galaxies is the HSS-LM (Ugryumov et al. 2003 (part I); Pustilnik et al. 2005, in preparation (part II)). The four XMD galaxies from the paper of Ugryumov et al. (2003) are already studied and used, e.g., for the problem of primordial helium (Izotov & Thuan 2004a). Here we report on a new galaxy HS 2134+0400 (J213658.95+041404.1), found in the HSS-LM (part II), which belongs to the group of eight the most metal-poor BCGs. We present for this object the results of spectrophotometry, and the derived physical parameters and element abundances. Discussing the properties of HS 2134+0400, we emphasize its atypical spatial position, distant from the cataloged luminous galaxies and their aggregates (the void environment), and suggest the possible implications of finding in voids this and other XMD galaxies.

2. Observations and reduction

The long-slit spectral observations were conducted with the SCORPIO multi-mode instrument (Afanasiev & Moiseev 2005), installed in the prime focus of the SAO 6 m telescope (BTA), during the night of November 8, 2004. The grism VPH550g was used with the 2K×2K CCD detector EEV 42-40 and the exposed region of 2048×600 px. This gave the range ∼3500–7500 Å with ∼2.0 Å pixel^{-1} and FWHM ∼12 Å along the dispersion. The scale and the total extent along the slit were $0''.18$ pixel^{-1} and $\sim 2'$, respectively. The slit with the position angle of 90° and the width of $1''$ (approximately along the major axis of the main body, see Fig. 2) crossed the bright central knot of the galaxy. One 15-min exposure was obtained. Before and after, the object spectrum was complemented by the reference spectra of He–Ne–Ar lamp for the wavelength calibration. Bias and flat-field images were also acquired to perform the standard reduction of 2D spectra. Spectral standard star Feige 34 (Bohlin 1996) was observed during the night for the flux calibration.

The standard pipeline with the use of IRAF[2] and MIDAS[3] was applied for the reduction of the long-slit spectra which included the next steps.

Cosmic ray hits were removed from the 2D spectral frame in MIDAS. Using IRAF packages from CCDRED, we subtracted bias and performed the flat-field correction. After that the 2D spectrum was wavelength-calibrated and the night sky background was subtracted. Then, using the data on the spectrophotometry standard star, the 2D spectrum was transformed to absolute fluxes. One-dimensional spectrum of the central H II region was extracted by summing up, without weighting, 11 rows along the slit ($\sim 2''$), where the principal line [O III]λ4363 for determination of T_e was above the level of $2\sigma_{\rm noise}$.

All emission lines were measured applying the MIDAS programs described in detail in Kniazev et al. (2004). Briefly, they draw continuum, perform robust noise estimation and fit separate lines by a single Gaussian superimposed on the continuum-subtracted spectrum. Emission lines blended in pairs or triplets were fitted simultaneously as blend of two or three Gaussians features. The quoted errors of singular line intensities include the following components. The first is related to Poisson statistics of a line photon flux. The second component is the error resulting from the creation of the underlying continuum, which gives the main contribution for the errors of faint lines. For the fluxes of lines in blends, an additional error appears related to the goodness of fit. The last term is related to the uncertainty of the spectral sensitivity curve and gives an additional error for the relative line intensities. For the presented observations this is 5%, and, hence, it gives the main contribution to the errors of the relative intensities of the strong lines. All these components were summed up squared. The total errors have been propagated to calculate the errors of all derived parameters.

[2] IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, In. (AURA) under cooperative agreement with the National Science Foundation (NSF).

[3] MIDAS is an acronym for the European Southern Observatory package – Munich Image Data Analysis System.

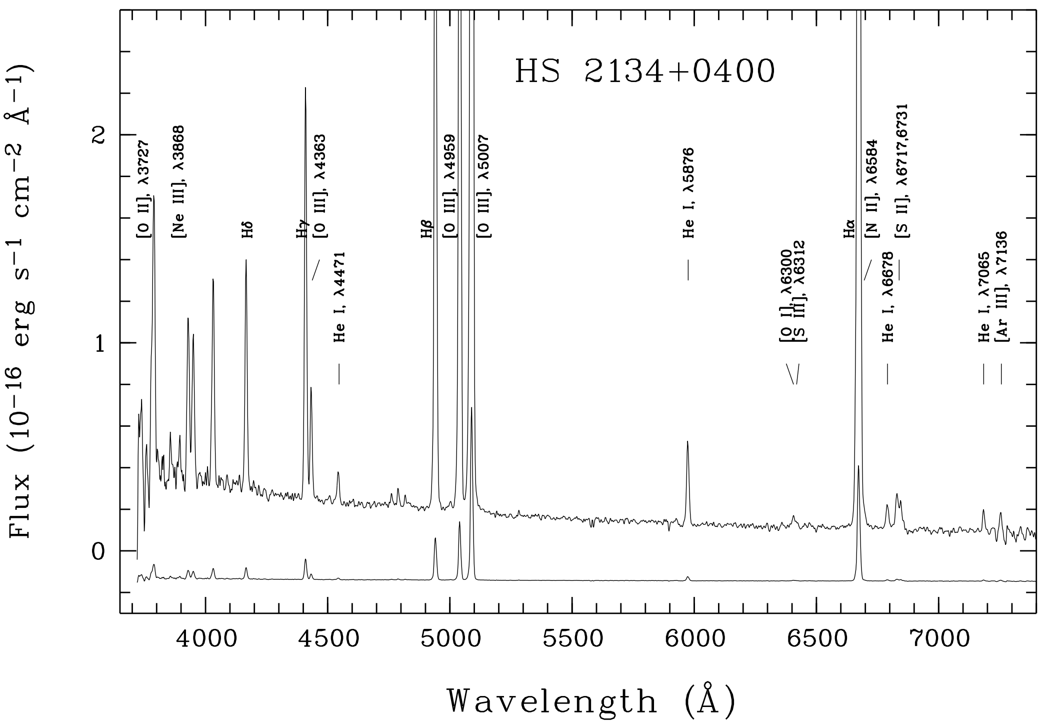

Fig. 1. The spectrum of HS 2134+0400 with the main lines marked. The same spectrum at the bottom is scaled down by a factor of 7 to show the relative intensities of the strong lines.

3. Results

3.1. Line intensities and element abundances

Relative intensities of all emission lines used for the abundance determination in the giant H II region of HS 2134+0400, as well as the derived C(Hβ), EWs of Balmer absorption lines, the measured flux in Hβ emission line and the measured heliocentric radial velocity are given in Table 1. The 1D spectrum of the object is shown in Figure 1. Extinction is low: C(Hβ) $\sim$0.1, what is well consistent with the extinction data for the majority of very metal-poor galaxies.

To derive the element abundances of species O, Ne, N, S, and Ar in the giant H II region of HS 2134+0400, we use the standard method from Aller (1984), and follow the procedure described in detail by Pagel et al. (1992) and Izotov et al. (1997). Chemical abundances and physical parameters are determined in the frame of the classical two-zone model of H II region (Stasińska 1990), as described in detail in our recent papers (Pustilnik et al. 2004b, Kniazev et al. (2004; 2005). The derived electron temperatures T_e and density N_e, as well as the abundances of oxygen, nitrogen, neon, sulfur, and argon are given in Table 2. The resulting heavy element abundances (in particular, the value of 12+log(O/H)=7.44$\pm$0.05) assign this BCG as the eighth most metal-poor galaxy of several thousand known BCG/H II galaxies in the nearby Universe.

4. Discussion and Conclusions

4.1. HS 2134+0400 in comparison to other very metal-poor BCGs

The element abundance ratios of Ne/O, S/O, N/O and Ar/O for HS 2134+0400 are consistent within (1.0–1.5)σ uncertainties with the abundance patterns for the group of the most metal-poor BCGs (Izotov & Thuan 1999). This fact is consistent with the production of all these elements in the XMD BCGs within the same massive stars along with oxygen.

The optical morphology of this faint galaxy ($B_{\rm tot}=19\overset{\rm m}{.}3$, Pustilnik et al. 2005, in prep.) with the bright central SF region, dominating the galaxy light, is quite typical of BCGs (Fig. 2). The outer isophotes are rather irregular and disturbed. There is a curved plume on the western edge. According to Telles et al. (1997) and Bergvall & Östlin (2002), such morphology is preferably related to the luminous BCGs ($M_{\rm B}$ of –17 to –20) and is suggested to be caused by strong interactions, and especially by mergers. Despite this BCG is not a very luminous ($M^0_B = -15\overset{\rm m}{.}1$), its merger nature is not excluded. To check this option, more detailed studies are necessary. In particular, several BCGs with M^0_B as low as $-14\overset{\rm m}{.}5$ to $-15\overset{\rm m}{.}4$ in the sample of 86 BCGs from the zone of the Second Byurakan Survey (Pustilnik et al. 2001b) were identified as having the 'merger' morphology. Moreover, some other XMD galaxies are clearly related

Table 1. Line intensities and the derived parameters in the giant H II region of HS 2134+0400

λ_0(Å) Ion	$F(\lambda)/F(\mathrm{H}\beta)$	$I(\lambda)/I(\mathrm{H}\beta)$
3727 [O II]	0.480±0.051	0.523±0.056
3869 [Ne III]	0.221±0.018	0.238±0.020
3967 [Ne III] + H7	0.251±0.016	0.268±0.025
4101 Hδ	0.256±0.015	0.270±0.022
4340 Hγ	0.464±0.025	0.482±0.029
4363 [O III]	0.126±0.010	0.131±0.010
4471 He I	0.038±0.006	0.039±0.006
4686 He II	0.009±0.003	0.009±0.003
4713 [Ar IV] + He I	0.019±0.005	0.020±0.005
4740 [Ar IV]	0.016±0.005	0.016±0.005
4861 Hβ	1.000±0.010	1.000±0.011
4922 He I	0.012±0.005	0.012±0.005
4959 [O III]	1.307±0.068	1.298±0.068
5007 [O III]	4.002±0.293	3.965±0.206
5876 He I	0.102±0.008	0.096±0.008
6300 [O I]	0.018±0.008	0.016±0.008
6312 [S III]	0.007±0.004	0.006±0.004
6548 [N II]	0.006±0.006	0.006±0.006
6563 Hα	3.004±0.153	2.740±0.152
6584 [N II]	0.020±0.006	0.019±0.006
6678 He I	0.030±0.007	0.027±0.006
6717 [S II]	0.048±0.009	0.044±0.008
6731 [S II]	0.040±0.009	0.036±0.008
7065 He I	0.022±0.005	0.020±0.005
7136 [Ar III]	0.022±0.006	0.019±0.005
C(Hβ) dex	0.12±0.07	
EW(abs) Å	0.00±2.27	
F(Hβ)[a]	45.8±0.6	
EW(Hβ) Å	214±11	
Rad. vel. km s^{-1}	5070±45	

[a] in units of 10^{-16} ergs s^{-1}cm^{-2}.

Table 2. Element abundances in HS 2134+0400

T_{e}(OIII)(10^3 K)	19.81±1.04
T_{e}(OII)(10^3 K)	15.63±0.76
T_{e}(SIII)(10^3 K)	18.14±0.86
N_{e}(SII)(cm^{-3})	236±570
O$^+$/H$^+$($\times10^{-5}$)	0.411±0.067
O^{++}/H$^+$($\times10^{-5}$)	2.310±0.290
O^{+++}/H$^+$($\times10^{-5}$)	0.027±0.012
O/H($\times10^{-5}$)	2.748±0.298
12+log(O/H)	7.44±0.05
N$^+$/H$^+$($\times10^{-6}$)	0.129±0.033
ICF(N)	6.686
log(N/O)	–1.50±0.12
Ne^{++}/H$^+$($\times10^{-5}$)	0.283±0.039
ICF(Ne)	1.190
log(Ne/O)	–0.91±0.08
S$^+$/H$^+$($\times10^{-7}$)	0.747±0.126
S^{++}/H$^+$($\times10^{-7}$)	1.930±1.107
ICF(S)	1.865
log(S/O)	–1.74±0.19
Ar^{++}/H$^+$($\times10^{-7}$)	0.519±0.143
Ar^{+++}/H$^+$($\times10^{-7}$)	1.267±0.435
ICF(Ar)	1.019
log(Ar/O)	–2.18±0.12

to the merger phenomenon. Some of them are also not luminous. They include, in particular, Dw 1225+0152 (M_{B} = –15; Salzer et al. 1991; Chengalur et al. 1995), HS 0837+4717 (Pustilnik et al. 2004b), SBS 0335–052 E and W (Pustilnik et al. 2001a, 2004a).

According to the starburst models of Schaerer & Vacca (1998) for the respective metallicity of z=0.001 and the standard Salpeter IMF, the measured value of EW(Hβ)=214 Å implies the age of the instantaneous SF burst of 3.2 Myr that corresponds to the maximum of Wolf-Rayet (WR) phase at this metallicity. This suggests that the higher S/N spectra can reveal the characteristic 'blue' WR bump and determine the fraction of WR stars relative to the full number of massive stars. This is an important observational parameter to test the models of massive star evolution in the very metal-poor environment.

Various evolutionary scenarios can lead to that small ISM metallicities. In particular, very low SF rate over the whole galaxy life will result in the small gas consumption and little ISM enrichment. Such a situation is expected in very low surface brightness galaxies. Indeed, almost all studied LSB dwarf galaxies with the oxygen abundances of

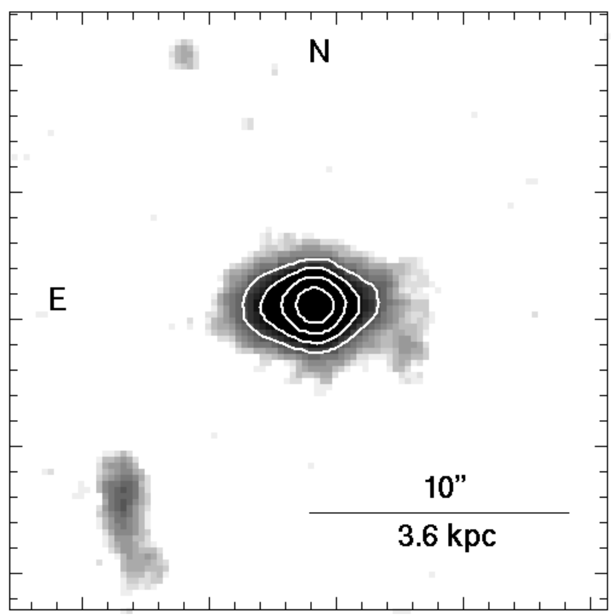

Fig. 2. B-band image of HS 2134+0400, obtained with the Wide Field Imager at the ESO 2.2 m telescope (see details in the forthcoming paper by Pustilnik et al. 2005b). Isophotes with the step of $1^m/\square''$ show the structure of the innermost region. At the adopted distance of 74 Mpc, the BCG East-West extent of $\sim9''$ corresponds to 3.2 kpc.

12+log(O/H) ≤7.50 (UGCA 20, UGCA 292, UGC 2684, AM 0624–261) appeared to have the old red stellar population (van Zee et al. 1996, van Zee 1997, Parodi et al. 2002), thus, they are old objects. On the other hand, several BCGs (or dIrr/BCG) with the lowest metallicities show no tracers of the old stellar population (I Zw 18, SBS 0335–052 E and W) and are currently considered as the best candidates for the genuine local young galaxies. By analogy, HS 2134+0400, as one of the lowest metallicity BCGs, also can belong to this group and therefore it deserves a more detailed multiwavelength study.

4.2. HS 2134+0400 as a 'void' galaxy

As shown, e.g., by Salzer (1989), Pustilnik et al. (1995), and Popescu et al. (1997), BCGs and H II galaxies, as subluminous objects, follow in general the spatial distribution of luminous galaxies ($L \geq L_*$). However, they show more scattering around the structures delineated by luminous galaxies, and do escape the densest regions. Only a small fraction of BCGs (15±5 %) fills in voids, the large regions completely devoid of luminous galaxies. Other subluminous late-type galaxies also partly fill in voids, forming some filamentary structures (e.g., Lindner et al. 1996).

This new XMD BCG is situated in the region of very low density of luminous galaxies ($M_B \leq M^*_B$=–19.6, for the accepted here H_0 = 72 km s^{-1} Mpc^{-1}). This region belongs to the outskirts of the huge Pegasus void, described by Fairall (1998). This void is characterized by the coordinates of its center (B1950) RA=22^h, Dec = +15°, cz = 5500 km s^{-1}, and by the void diameter of 3000 km s^{-1} (∼40 Mpc). HS 2134+0400 is quite far from the void center, closer to its SW rim, not far from its foreground edge. We have examined the environment of this galaxy using the Updated Zwicky Catalog redshifts (Falco et al. 1999) and the additional information on fainter galaxies from NED. The nearest object to HS 2134+0400 is the luminous galaxy pair CGCG 402-013 at D=4.0 Mpc (NGC 7102, $M_{\rm B}$ = −19.7). The next nearest galaxies are CGCG 402-004 at 4.4 Mpc ($M_{\rm B}$ = –18.5) and UGC 11792 at 4.8 Mpc ($M_{\rm B}$ = –18.6). All other known galaxies are at the distances more than 6 Mpc. It is worth noting that HS 2134+0400 is not the only XMD galaxy found in the Pegasus void. The BCG HS 2236+1344 with 12+log(O/H)=7.47 (Ugryumov et al. 2003, Izotov & Thuan 2004a) also falls in this void. It is situated on the opposite side of the void, somewhat closer to its center.

How common are very low metallicity galaxies in voids? The quantitative comparison of the metal content of dwarf galaxies in voids and in the denser environment still waits for the good quality O/H determinations performed for large well selected samples. Below we mention several other examples of a dozen XMD galaxies found by us in voids (paper in preparation), which probably will stimulate the studies of this issue. In particular, in one of the nearest small voids, the Lynx-Cancer one, having a diameter of ∼800 km s^{-1}, three XMD galaxies are discovered with 12+log(O/H) from 7.21 to 7.65 (Pustilnik et al. 2003, 2005a). Several other known XMD BCGs, like HS 0837+4717 (Pustilnik et al. 2004b) also fall in voids delineated by luminous galaxies.

One more interesting example is that of two XMD galaxies falling close to the center of a known void. These are HS 1313+4521 with 12+log(O/H)=7.57 and $V_{\rm hel}$=3449 km s^{-1} (Pustilnik et al. 2005c, in preparation) and KISSR 1490 (1311+4418) with 12+log(O/H)=7.56 and $V_{\rm hel}$ = 3559 km s^{-1} (Lee et al. 2004). The both dwarf galaxies are situated within ∼3 Mpc from the center of the void 'C4' defined by Lindner et al. (1995). Its center coordinates (B1950) correspond to RA = 13^{h}19^m, Dec = +47.5°, cz = 3690 km s^{-1}, its diameter corresponds to 1500 km s^{-1} (∼20 Mpc).

If the appearance of many XMD galaxies in voids is not occasional, whether some natural explanations for such a correlation can be suggested? Probably yes. Despite of such cases were not described in the literature at that time, Peebles (2001) suggested that unusual objects similar to SBS 0335–052 would be natural to find in voids. Our discoveries of many XMD galaxies in voids seems proves his prediction. In the frame of the Cold Dark Matter cosmology, the galaxies formed in voids, should be predominantly of lower mass and retarded in their formation epoch in comparison to the galaxies from the average and higher density regions (e.g., Gottlöber et al. 2003). In the frame of the popular hierarchical galaxy formation scenario (e.g., White & Frenk 1991), due to the reduced galaxy density in voids, a part of these dwarfs can belong to the group of galaxies, experienced very few, or even no collisions during their life. They will differ quite much from the more common galaxies which past through many interactions and/or mergers. In particular, one could expect that a fraction of void galaxies can survive in their nascent state, avoiding any significant interaction that triggers intensive star-forming episodes and causes the additional ISM metal enrichment.

4.3. Conclusions

Summarizing the presented observational results and the discussion above, we draw the following conclusions:

– The oxygen abundance in the giant H II region of the blue compact galaxy HS 2134+0400 is of 12+log(O/H)=7.44±0.05 dex, it belongs to the eight most metal-poor BCGs.
– The heavy element abundance ratios S/O, Ne/O, N/O and Ar/O are well consistent with the average values derived on the small group of the most metal-poor BCGs.
– HS 2134+0400 falls to the region with the low density of luminous galaxies, at the outskirts of the large Pegasus void, in which one more very metal-poor BCG HS 2236+1344 is found.

- These two objects, along with many other XMD galaxies discovered in voids, may comprise a representative group of the void galaxy population. The existence of such a group would indicate the importance of the effect of global environment on the chemical evolution of low-mass galaxies.

Acknowledgements. The authors thank A.V. Moiseev for the help in observations with SCORPIO. SAP, AGP and AVU acknowledge the partial support from Russian state program "Astronomy". This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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